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P. Bradshaw, Johnston, J.P., and Moffat, R.J.

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This project investigated the mechanisms responsible for the known increases in shear stress and convective heat transfer when a turbulent boundary layer flows over a concave wall compared to a similar flow over a flat wall. In addition, the effects of grid-generated free-stream turbulence (FST level < or = 7.5%) were examined for flat- and concave-wall TBL's. The work was conducted in a large scale boundary layer using low-speed water flow. Momentum thickness Re was = 1400. Surface heat transfer rate was measured with a constant temperature metal surface and by use of a liquid crystal surface. Temperature profiles were obtained by miniature thermocouple probe down to y+ = 3 and all three velocity components by a 3-D, laser velocimeter down to y+ = 7.

Heat transfer and wall shear stress were both found to be augmented by curvature and free-stream turbulence applied separately, but the combined effect of curvature and

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19. ABSTRACT (continued)

FST is not simply the sum of the individual effects. In the case of wall stress, the effects of curvature are much larger than FST effects once the flow develops downstream. The nature of the interaction is being investigated using a working hypothesis based on the ideas of active (Reynolds stress producing) and inactive (uncorrelated) turbulence. Some evidence suggests that increase in inactive FST can stimulate only a limited increase (order 25%) in Cf. However, for the moderate levels of FST used in this study, no such saturation process exists to limit the increase in surface heat transfer rate; St appears to increase steadily as FST increases.

Other results of interest concern the effects of fluid Prandtl number (e.g. 5 to 7.5 in water, 0.7 in air) on heat transfer in a turbulent boundary layer. In particular, it is shown that the distribution of turbulent Prandtl number is the same in both fluids across the layer, Prt is unity down to $y+ = 20$, but rises sharply in the sublayers to values of 1.5 to 1.8 near $y+ = 5$. This distribution, when used in the simple, two-dimensional, boundary layer computational code STAN5 (and later versions) gives very good predictions of surface heat transfer. Conventional correlations ostensibly account for the effects of Prandtl number by a simple multiplication term ($Pr^{0.3}$, for example) applied to a friction factor prediction equation. We find this approach to be quite inaccurate. For example, the Reynolds number dependence usually shown as $Re^{-0.2}$ for both air and water should, in fact, be $Re^{-0.12}$ in water, although the exponent -0.2 is correct for air.

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The Heat Transfer and Fluid Dynamics of Concave Surface Curvature

P. Bradshaw, J. P. Johnston, R. J. Moffat
Department of Mechanical Engineering
Stanford University
Stanford, CA 94305

21 April 1988

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FORWORD

This document is arranged to permit Bradshaw, who joined the program during its last four months, to report his items separately in Section 5. Details of his prior work in this field are reported separately.

1. GOALS

1.1 Introduction

Kreith* first showed, in 1955, that concave curvature increased heat transfer, although the fact that curvature affected the turbulence structure had been known since the early 30's. Between 1955 and 1967, there does not appear to have been much activity. In 1967 Schneider and Wade measured heat transfer in a curved-duct flow, and in 1968 Thomann made local measurements of boundary-layer heat transfer in a supersonic flow with convex and concave curvature. In every instance, concave curvature resulted in an increase in heat transfer. The increase was assumed by many to be the direct consequence of streamwise vortices within the boundary layer, caused by a Taylor Gortler instability, but there was dissent. Eskinase and Yeh (1956) reported an increase in heat transfer, but no evidence of streamwise vortices. The issue has become increasingly important as aircraft engine designers have pressed closer and closer to the limits of assurable prediction of heat transfer. It is desirable to be able to predict the heat-transfer coefficient within 5% on a turbine blade, yet this cannot be done at the present state of the art. Most of the current prediction programs for boundary-layer heat transfer are two-dimensional. If Taylor-Gortler vortices are important in the concave-wall boundary layer, then three-dimensional codes will have to be developed. On the other hand, if the increase in heat transfer is a result of a generally increased turbulence activity, but still two-dimensional, then existing codes can be simply modified to acknowledge the curvature effect, and no major changes in computational philosophy need be undertaken.

The original objective of this work was to identify the mechanism whereby concave curvature increases the heat transfer through a turbulent boundary layer. This involved careful documentation of the fluid mechanics and of the heat transfer. It was necessary to establish a well-qualified flow on a concave surface, demonstrate that the heat transfer was increased, and then determine the fluid mechanic and thermal behavior of the boundary layer carefully enough to establish whether or not streamwise vortices played an important role. As in most convective heat-transfer problems, the fluid mechanics had to be thoroughly understood before the heat-transfer study began.

A second objective of the program added after its start was to investigate the effects of increased levels of freestream turbulence on the flow and heat transfer when this additional complexity is combined with the effects of concave curvature. In particular, it is of interest to see if there are significant interactions between the two effects, both of which increase momentum transfer (wall shear stress) and heat transfer by themselves.

1.2 Objectives of the Fluid-Mechanics Study

As a result of the past work on this project (Jeans and Johnston 1982, 1983, and Barlow and Johnston 1985) a much clearer picture of the effects of concave-curvature on turbulent boundary layers has emerged. With a better understanding of concave curvature, an investigation of the effects of free-stream turbulence on concave turbulent boundary layers was begun. This new direction is a relevant one; previous researchers have shown that free-stream

* References listed here are in Reports HMT-35 and MD-47, listed at the end of this section.

turbulence over a flat plate can increase skin friction by 25% and Stanton number up to a factor of five. This direction allows us to build on the extensive data base compiled by Barlow, so that the effects due to free-stream turbulence can be separated from those due to streamwise curvature.

1.3 Objectives of the Heat-Transfer Study

The objective of this heat-transfer study is to determine the mechanisms by which concave curvature increases heat transfer and to develope a mixing-length model to predict the observed heat transfer behavior. Past work on this project (Simonich and Moffat, 1982) using liquid crystal thermal visualization concluded that the increase in average heat transfer was not the result of locally increased heat transfer coefficient produced by a system of streamwise vortex structures. This result showed that the effects of curvature could be modelled by a two-dimensional mixing-length computer code and reopened the question of the nature of the mechanism(s) producing the increase in heat transfer coefficient.

Differences are to be expected between the thermal boundary layers in water and in air due to the difference in Prandtl number, and there are correlations available which purport to account for the Prandtl number effect. A series of measurements was planned for the flat-plate, development section of the channel to baseline the flat-plate water thermal boundary layer and confirm the Prandtl number effect. Such confirmation would allow the effects of concave curvature on heat transfer to be separated from those of increased Prandtl number with confidence.

The specific tasks for the heat transfer portion of the project were: (1) completion of the aluminum heat transfer surface for the flat and curved test sections, (2) measurement of baseline Stanton number data, (3) measurement of the mean and fluctuating temperature profiles in the flat and curved sections, (4) development of a technique to measure correlations between temperature and velocity, (5) dye injection and/or hydrogen bubble flow visualization of large scale inflow and outflow regions in the curve, (6) construction of one flat and one curved liquid crystal panel to be used with the new heat transfer surface, (7) to perform a "first look" investigation of the effects of grid-generated turbulence on the surface heat flux and the thermal boundary layer in the flat and curved sections of the channel.

2. ACCOMPLISHMENTS

2.1 Fluid Mechanics

Most of the goals of the work originally proposed have been accomplished. All work was carried out experimentally in a low speed water flow facility built especially for this research, Jeans and Johnston (1982), and further developed by Barlow and Johnston (1985, 1988).

In summary, the accomplishments for the period 1986-88 include:

(i) The development of a measurement system that allows the simultaneous measurement of all three components of flow velocity (u, v, w) using laser Doppler velocimetry. A contribution to the technique of Reynolds stress measurement using LDV systems has been prepared as a paper, Johnson and Barlow (1989).

(ii) The completion of a set of measurements of mean velocity profiles and profiles of all six Reynolds stresses in a flat-wall turbulent boundary layer at $Re\theta = 1400$, and along a concave-wall turbulent boundary layer. The original work by Barlow used a two-component LDV system where only u and v could be obtained. Barlow's work has been repeated and in addition the w,

the spanwise, velocity component obtained. These data penetrate deep into the wall layers, and give accurate results for the Reynolds stresses at the edge of the viscous sublayer, down to $y^+=7$. In our recent work, we compared the measurements to the computed, direct simulations of a flat-plate turbulent boundary layer at $Re_\theta = 1410$, Spalart (1988). The agreement between our new data, the original 2-D data of Barlow, and the simulation is excellent across the whole boundary layer.

(iii) The effects of grid-generated free-stream turbulence on the turbulent boundary layers over the flat-wall, and in the concave-wall regions.

For these studies, a biplaner grid constructed of 1/2 inch wide square bars with a mesh spacing (M) of 2.5 inches was inserted across the channel at an upstream station. The grid Reynolds number $U_\infty M/\mu = 10{,}500$. At a downstream distance of $x/M = 10$, individual grid bar wakes could no longer be discerned and the turbulence was nearly isentropic with a free-stream level of $u'/U_\infty = 7.5\%$. In the flat walled portion of the channel, turbulence decayed downstream to $u'/U_\infty = 5\%$ at $x/M = 19$. However, when the grid was placed just upstream of the curved portion of the channel, the rate of decay of turbulent kinetic energy was less than the rate of decay in the flat-walled channel. Measured free-stream turbulence energy distribution is shown in Figure 2.1.1 for the two cases. The reduction of decay rate in the curved region was explained by examination of extra terms in the equation for turbulence energy when expressed in streamline (S-N) coordinates. There is additional production due to the extra rate of strain resulting from curvature, $\partial V/\partial x = U/R$ along curved streamlines.

The grid-generated turbulence was used to study the development of the turbulent boundary layer in the flat-walled and the curved regions of the channel. For the flat region, mean velocity profiles and wall friction coefficients, Cf, were obtained at the downstream station ($Re_\theta = 1400$) with the grid located at various upstream stations to give u'/U_∞ values up to 7.5%. Complete velocity and Reynolds stress profiles were obtained for the cases of 5 and 7.5%, respectively. For similar measurements over the concave wall, the grid was moved to various stations ahead of the curved region so that the 5% case was produced at four stations in the curve (15, 30, 45, and 60 degrees of turn). The corresponding "natural" low-turbulence flat- and curved-wall cases used for comparison have $u'/U_\infty = 1\%$. These same flow conditions were used to obtain the heat transfer results, section 2.2 below.

Figure 2.1.2 shows the effects of free-stream turbulence on the increase in Cf for flat-wall flow. For comparative purposes the coordinates suggested by Hancock and Bradshaw (1983) are used. In addition, we have applied the low Reynolds number modification of Blair (1983) to our results, the solid squares. This correlation is supposed to account for both level and length scale effects in the free-stream turbulence. Our data falls below earlier results, and suggests that further increases in turbulence level may cause no further increases in wall shear stress. As pointed out below, *no such limit* on the increase of wall heat transfer is observed.

The reason for a "saturation" effect on Cf, and not on heat transfer is being sought, and a qualitative model invoking the concepts of active and inactive turbulence is suggested (Townsend, 1961 and Bradshaw, 1967). Our application of the concept is that free-stream turbulence must excite or stimulate additional active motions (motions that produce Reynolds shear stress, $-\langle u'v'\rangle$) to cause an increase in Cf. There is a limit to the amount of added stress that can be produced from the sublayer vorticity bed since dissipation also increases rapidly as the free-stream turbulence interacts with the bed. Natural active and inactive motions produced by the layer itself and all motions induced by free-stream turbulence in the viscous sublayer contribute to the steepening of the instantaneous wall temperature gradients which give rise to increased heat transfer. Since there is no intervening inner layer production/dissipation mechanism for thermal effects, there is no reason to believe that wall heat transfer will be limited in the same way as wall stress.

The case for this model is still not proven, but some of the other data for the flat-wall flow add weight to the concept. In the case of natural flow (1%) and the 5% free-stream turbulence flow, the profiles of the turbulence Reynolds stresses, scaled on inner variables, collapse universally below y+ of 50 when plotted in wall layer coordinates. However, the w' component deviates upward from a universal curve in the 7.5% case, see Figure 2.1.3. Spectra of the turbulent shear and normal stresses at y+ = 14 are compared in Fig. 2.1.4. The increase in the spanwise, w', fluctuation levels are noted in the lower frequency range, whereas the spectra of the other components don't change. This behavior is believed to be consistent with the active/inactive motion concept. Somewhere between 5.0 and 7.5% the active motions approach a saturated state, but inactive motions in the inner layer can still increase, and consequently universal inner scaling laws will not hold for all components. Many details are still under study and will be reported later.

The work on the combined effects of 5% level of free-stream turbulence and concave wall curvature are still being analyzed too, but Figure 2.1.5 gives the overall results on the fractional increase in Cf versus downstream distance, measured in degrees of turning angle starting at the end of the flat wall as the flow moves into the curve. Also shown are flat-wall fractional increases adjusted at each point to account for actual free-stream turbulence length scales according to the Hancock and Bradshaw (1983) method. In each case, the reference value, Cfo is obtained from the simple flat-wall, low-turbulence formula shown by using measured momentum thickness Reynolds numbers. The combined effects give a greater increase in Cf than the effect of turbulence alone. At the first curved-wall station (15 degrees) the two effects are nearly the same in magnitude, both giving an added 15 percentage points to Cf. However as the curvature effects develop downstream, the additional increase caused by free-stream turbulence diminishes. This result may also be explained by the active/inactive turbulence concept, but we need to study the issue further. It is worth noting that wall layer similarity is preserved at all stations along the curved wall. In addition, it has been shown by Barlow and Johnston (1988), for low-turbulence free-stream flow, that the concave-wall instability mechanism leads to higher turbulence levels. These levels are marked by a very high degree of u'v' correlation in the outer parts of the boundary layer, a situation quite different from the case of free-stream turbulence interacting with a flat-wall boundary layer where Reynolds shear stresses are produced primarily in the wall-layer regions.

2.2 Heat Transfer

The Simonich and Moffat experiment was expressly designed to look for evidence of streamwise structures, and was not as well suited to accurately measuring the average heat transfer. In order to make accurate mean value measurements, the liquid crystal surface used by Simonich and Moffat was replaced with a set of electrically heated aluminum sections. The new surface had two advantages: (1) the uniform temperature plates are easier to construct and far less prone to failure during operation, and (2) they produce a more uniform boundary condition and improve the accuracy with which the average Stanton number can be measured. In 1987 the new aluminum surface was installed and baseline heat flux data was acquired. The Stanton number at the 60 degree point in the curve was found to be about 32% higher that at the same streamwise position in a flat plate boundary layer. The measurement agreed well with the estimates of average Stanton number made by Simonich using the liquid crystal panels, and has considerably less uncertainty.

A rapid response thermocouple probe was designed for making single point measurements in the thermal boundary layer. The response of the probe was such that it could follow the turbulent thermal fluctuations and it could be positioned within 3 y^+ units from the wall. Profiles of mean temperature in the flat-plate section of the channel were used in the baseline study. These, along with profiles of u^+ and u'v' from the present hydrodynamic study, were used to calculate the near-wall distribution of turbulent Prandtl number for the water

boundary layer. The results of this calculation (shown in Figure 2.2.1) agree well with data obtained by Blackwell et al and Orlando et al for air boundary layers, including the rise in Pr_t in the sublayer.

Profiles of the fluctuating temperature in the flat section showed a maximum RMS value of about 16% of the boundary layer temperature difference occurring at about $y^+ = 7$, a position well below the expected value of $y^+ = 13$ to 15 for an air boundary layer. This is an important Prandtl number-related effect and is demonstrated by the comparison shown in Figure 2.2.2 of the data from the present study to that of Zukauskas et al for an air boundary layer at approximately the same Reynolds number. The RMS temperature fluctuation reflects a convective effect: fluid particles from origins at different temperatures passing through the measuring volume. The high RMS values observed here are caused by the very high slope of the temperature profile in the viscous sublayer of a water flow (Prandtl number of approximately 6). Fluid particles moved normal to the wall by vertical velocity fluctuations produce large temperature fluctuations even though the velocity fluctuations are smaller in the sublayer than at $y^+ = 13$ to 15.

Measurements of instantaneous correlations between velocity and temperature were attempted using the two-component LDA system for measurement of u' and v'. Fluctuations in the index of refraction on the order of 2 parts in 10,000 (caused by temperature fluctuations along the beam paths) caused the laser measuring volume to be unstable. The LDA system cannot be used to measure velocity in the heated water boundary layer unless some method can be devised to reduce this effect. Velocity-temperature correlations cannot be made with the current system, and the current approach.

A video tape was made of dye injection flow visualization. The tape shows the near-wall structure in the flat and curved sections and the outflow regions in the curve.

A study of the effect on the Stanton number of the introduction of grid-generated turbulence was performed after the new test surface was qualified. This work exactly paralleled the high turbulence work done in the fluid-mechanics study and provided a "first look" at the combined effects of curvature and free-stream turbulence to guide further research in this area. An increase in Stanton number of 34% was measured at a streamwise position on the flat plate where the free-stream turbulence intensity was 5%. At 60 degrees into the curve with a 5% free-stream turbulence level, Stanton number was increased by 21% over the value obtained due to curvature alone. These results indicate that the coupling of the effects of high turbulence and concave curvature cause a Stanton number enhancement which is not simply the sum of the effects taken separately. The distribution of mean temperature (made non-dimensional on inner-layer variables) was fuller with free-stream turbulence present, but the distribution of the RMS temperature fluctuations showed no substantial change.

In 1988, with the "first look" at the combined effects of curvature and free-stream turbulence completed, the work progressed to studying the effects of concave curvature (in the presence of high Prandtl number) in more detail. The channel was operated with constant free-stream and wall temperatures to insure a constant Prandtl number for a series of experiments. Wall heat flux data were taken in the flat development station and through 60 degrees into the curve. Profiles of mean and fluctuating temperature were taken at two stations on the flat wall and at four equally spaced stations in the concave curve. These data were analyzed to determine Stanton number, and to investigate the changes in the structure of the thermal boundary layer with curvature. An important part of the work was predicting the flat plate results with Stan6, a mixing-length-based computer code written by Professor William Kays and validated for air boundary layers. The results from Stan6 agreed well with the flat plate data when the appropriate molecular and turbulent Prandtl numbers were used in the computation. Work was begun on analyzing the profiles of velocity and temperature in the curve to determine a mixing-

length model for concave curvature. The mixing-lengths in the near-wall region appear to adjust immediately to concave curvature, but the outer region adjusts more slowly, with no asymptotic behavior yet observed. The thermal profiles (shown in Figure 2.2.3) yielded values for turbulent Prandtl number that fell as the flow evolved through the curve. In convex curvature, the turbulent Prandtl number increases in the streamwise direction. This model will be included in Stan6 to investigate the prediction of the heat transfer enhancement due to curvature.

Temperature spectra were taken both in the sublayer and log layer at one flat station and at 60 degrees in the curve. Figures 2.2.4 and 2.2.5 show the four spectra plotted against frequency non-dimensionalized on inner layer variables. While the sublayer spectra are similar, the spectrum measured in the log region at the 60 degree station shows higher RMS values of the temperature fluctuations at low frequencies. The same results was shown by Barlow and Johnston for spectra of v'. This shift in the energy spectra is believed to be evidence of the large-scale lateral motions of the transient roll cells. The spectra of temperature and v' (from Barlow and Johnston) taken in the sublayer do not show a structural change. This result indicates that the roll cells do not penetrate the sublayer directly and therefore provides further confirmation of the thermal visualization results of Simonich and Moffat.

3. REPORTS AND PAPERS FROM THIS STUDY

3.1 Work Prior to 1986

Barlow, R. S., and Johnston, J. P., "Roll-Cell Structure in a Concave Turbulent Boundary Layer," AIAA-85-0297, presented at AIAA 23rd Aerospace Sciences Meeting, Reno, January 14-17, 1985.

Barlow, R. S., and Johnston, J. P., "Velocity Spectra of Turbulent Boundary Layers on a Concave Surface," Fifth Symposium on Turbulent Shear Flows, Cornell University, August 1985.

Barlow, R. S., and Johnston, J. P., "Structure of Turbulent Boundary Layers on a Concave Surface," Report MD-47, Thermosciences Div., Mech. Engrg. Dept., Stanford, CA, 1985.

Jeans, A. H., and Johnston, J. P., "The Effects of Concave Curvature on Turbulent Boundary-Layer Structure," Structure of Complex Turbulent Shear Flow (R. Dumas and L. Fulachier, eds.), Springer-Verlag, 1983, pp. 89-99.

Jeans, A. H., and Johnston, J. P., "The Effects of Streamwise Concave Curvature on Turbulent Boundary-Layer Structure," Report MD-40, Thermosciences Div., Mech. Engrg. Dept., Stanford University, June 1982.

Jeans, A. H., and Johnston, J. P., "Turbulent Boundary Layers on Concave Walls," 16 mm film supplement to Report MD-40. Contact J. P. Johnston, Mech. Engrg. Dept., Stanford Univ., Stanford, CA 94305.

Simonich, J. C., and Moffat, R. J., "A New Technique for Mapping Heat-Transfer Coefficient Contours," Review of Scientific Instruments, 53:5, May 1982, pp. 678-683.

Simonich, J. C., and Moffat, R. J., "Visualization of the Heat Transfer through a Turbulent Boundary Layer on a Concave Wall," HMT-35, Mech. Engrg. Dept., Stanford University, August 1982.

Simonich, J. C., and Moffat, R. J., "Visualized Heat Transfer from a Turbulent Boundary Layer on a Concave Wall," 16 mm supplement to Report HMT-35.

Simonich, J. C., and Moffat, R. J., "A Liquid-Crystal Technique for Visualization of Convective Heat Transfer," 16 mm supplement to the article in the Review of Scientific Instruments.

3.2 Completed Work, Current Grant

Barlow, R. S., and Johnston, J. P., "Structure of a Turbulent Boundary Layer on a Concave Surface, J. Fluid Mechanics, Vol. 191, 1988, pp. 137-176.

Barlow, R. S., and Johnston, J. P., "Local Effects of Large-scale Eddies on Bursting in a Concave Boundary Layer," J. Fluid Mechanics, Vol. 191, 1988, pp. 177-195.

3.3 In Preparation, Current Grant

Hollingsworth, D.K., "The Effects of Concave Curvature on the Turbulent Thermal Boundary Layer in Water," Ph. D. dissertation, August, 1989.

Hollingsworth, D.K., Boehman, A.L., Smith, E.G., and Moffat, R.J., "Measurement of Temperature and Heat Transfer Coefficient Distributions in a Complex Flow Using Liquid Chrystal Thermography and True-Color mage Processing," submitted to the Heat Transfer Division of ASME for the Winter Annual Meeting, Dec. 1989.

Hollingsworth, D.K., Kays, W.M., and Moffat, R.J. "The Measurement and Prediction of Heat Transfer in a Turbulent Boundary Layer in Water," to be presented at the 7th Symposium on Turbulent Shear Flow, Stanford, CA, August 1989.

Johnson, P. L., "Effects of Grid-Generated Turbulence on Turbulent Boundary Layers over Flat- and Concave-walls," Ph. D. dissertation, August, 1989.

Johnson, P .L., and Barlow, R. S., "Effects of Finite Measuring Volume Length on Laser Velocimetry Measurements in a Turbulent Boundary Layer," Submitted to Experiments in Fluids, 1989.

Johnson, P. L. and Johnston, J. P., "Active and Inactive Motions in a Turbulent Boundary Layer - Interactions with Free-Stream Turbulence," to be presented at the 7th Symposium on Turbulent Shear Flow, Stanford, CA, August 1989.

4. PERSONNEL

In addition to the three principal investigators, there have been two graduate students, both candidates for the Ph. D., working on the program since its inception.

- o Paul L. Johnson, Ph.D. degree expected summer 1989.
- o D. Keith Hollingsworth, Ph.D. degree expected summer 1989.

5. FREE-STREAM TURBULENCE (Bradshaw's Contribution)

Continuation of Imperial College work (original subcontract to Purdue University under AFOSR F49620-87-k-0008)

5.1 Present Position

A paper on the Imperial College work by Baskaran and Bradshaw has been accepted for presentation at the 7th International Symposium on Turbulent Shear Flow: it concentrates on the effect of the wake of an upstream body (airfoil/blade or bar) which we found to be mainly a reduction in drag or heat transfer (in other words, the reduction in mean velocity in a wake outweighs the effect of wake turbulence as such). In a real turbomachine, drag would be roughly proportional to circumferentially-averaged (velocity squared), and this would increase for given mass flow rate, because of increases in velocity between the blade wakes. On the other hand, heat transfer would be - again roughly - linearly proportional to circumferentially-averaged velocity and would therefore be unaffected to first order: thus effects of turbulence as such could be distinguished. The paper also presents results for the effect on a flat-plate boundary layer of the wake of a rod inclined at a finite roll angle, representative of turbomachines with non-radial blades.

The proposal for continuation of Imperial College research involved measurement of joint statistics of the velocity and temperature fluctuation fields in the boundary layer behind a turbulence generator simulating free-stream turbulence in a turbomachine. In the absence of a Stanford PhD student, work has been carried on by MS Fellowship students, who are required to carry out nine hours a week of "directed study" (at no cost to the present contract).

In the Fall quarter, Mr S. Hiebert studied the flow round the sharp leading edge of the flat plate used by P. Maciejewski for studies of the effect of "free stream" turbulence generated by a jet. A smoke wire was used to emit a sheet of smoke into the flow near the leading edge, for one or two seconds at a time. (A continuous smoke source would have been preferable, but is not acceptable in this open laboratory.) Reversed flow was found downstream of the leading edge during most of the smoke-wire runs, and it appeared that the recirculation region extended beyond the region where the smoke was visible, i.e. at least 0.1-0.2m downstream of the leading edge. The question of the role of the recirculation in the large increases in Reynolds analogy factor found by Maciejewski has not of course been answered by the smoke tests, but reversed flow makes a positive contribution to heat transfer even though it makes a negative contribution to time-average skin friction, and so intermittent separation and flow reversal would be qualitatively expected to increase Reynolds analogy factor.

In the Spring quarter, Mr J. Kulick has constructed a heat-transfer plate similar to that used at Imperial College, using 0.001" x 1" steel shim heating strips sandwiched between two sheets of 3/8" particle board. The strips are closely spaced (typical gap 0.005") and connected in series electrically, so that the configuration resembles a resistance strain gauge and the heat transfer through either surface of the plate is (a) uniform (b) equal to half the electrical power input. The plate has been tested in still air and has now been mounted in a fully-developed duct flow for shakedown tests. Mr Kulick has requested to continue the work next quarter, when the 30in. x 30in. tunnel and hot/cold-wire equipment should be ready. He intends to stay on for a PhD, but he is not bound to choose this topic.

The construction of the 30 in x 30 in blower tunnel has been supported partly by AFOSR under this contract, partly by The Boeing Company, and partly by Stanford School of Engineering funds. All parts except the working section are now complete; final assembly, including mounting of the screens and honeycomb, is in progress, and the working section will

be built on simple erector-set principles very shortly. MS students, taking a course on "Experimental Methods in the Thermosciences", will calibrate the tunnel as a laboratory project. Hot-wire circuit boards (also partly financed by AFOSR) are now ready. The circuit, designed by Dr. S. Kauh during a Sabbatical visit to the Department, is also usable for "cold wire" resistance thermometers and has the useful feature that several wires can be connected to a common ground line, simplifying the connections of a multi-wire probe.

5.2 Future Plans

A final choice of turbulence generator for the detailed measurements of joint statistics of velocity and temperature fluctuations - using hot and "cold" wires - has not yet been made. The contract objective is to study anisotropic free-stream turbulence typical of turbomachines. Accepting that the main effect of wakes from upstream blades is to reduce the mean velocity, we contemplate subtracting out this effect by generating inhomogeneous turbulence with negligible mean velocity variation. This would be done using a "graded grid" of bars, with large, widely-spaced bars for half the span and a fine screen, producing little turbulence, covering the other half-span. If the pressure drop through the two halves is the same, this will produce a step change at mid-span, from nominally-isotropic turbulence to negligible turbulence, with zero change in mean velocity. In a linear system, the response to a step change would yield enough information to predict the general response: this is not true in nonlinear systems like turbulence, but response to a step change is still meaningful. Current knowledge does not even make clear whether correlations for the effect of isotropic free-stream turbulence can cope with anisotropic turbulence.

In the summer quarter, at a time to be arranged, a new Master's student, Ms M. Coil, will commence full-time work: at the start of the academic year she will revert to part-time work, but she will make use of the above-mentioned equipment development and part-time MS student work, so it is hoped that most of the contract objectives can be achieved by the end of the contract year.

6. INTERACTIONS

Various components of the work have been presented formally on a number of occasions at technical meetings such as the annual meetings of the Division of Fluid Mechanics of the American Physical Society, and informally at seminars and workshops at Stanford and elsewhere. The important papers and symposia presentations are listed in section 3. above.

Our main Air Force contact has been with Mr. Richard Rivir of the Aero Propulsion Lab, WPAFB, Ohio. Both Professors Johnston and Bradshaw have visited his laboratory. Professor Moffat has worked with him on various occasions in connection with activities of the Heat Transfer Division of ASME.

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Zukauskas, A., A. Slanciauskas, and J. Karni, Heat Transfer in Turbulent Fluid Flows, Hemisphere Publishing, Washington, 1987.

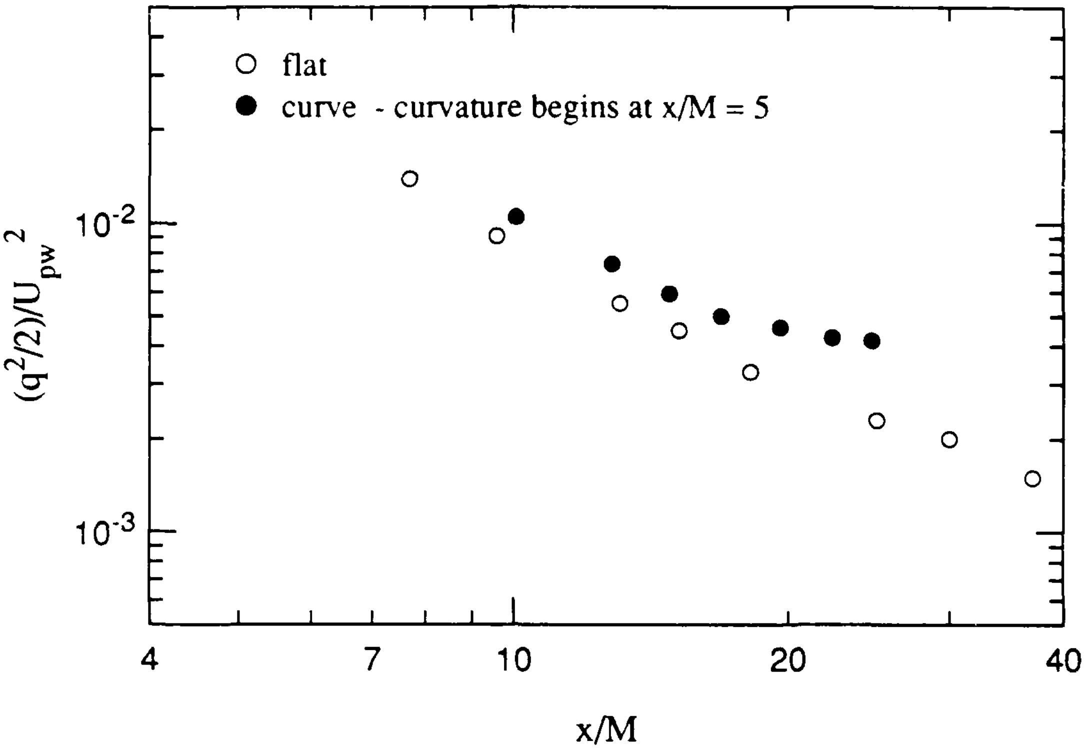

Fig. 2.1.1. Comparison of decay of grid turbulence in flat and curve.

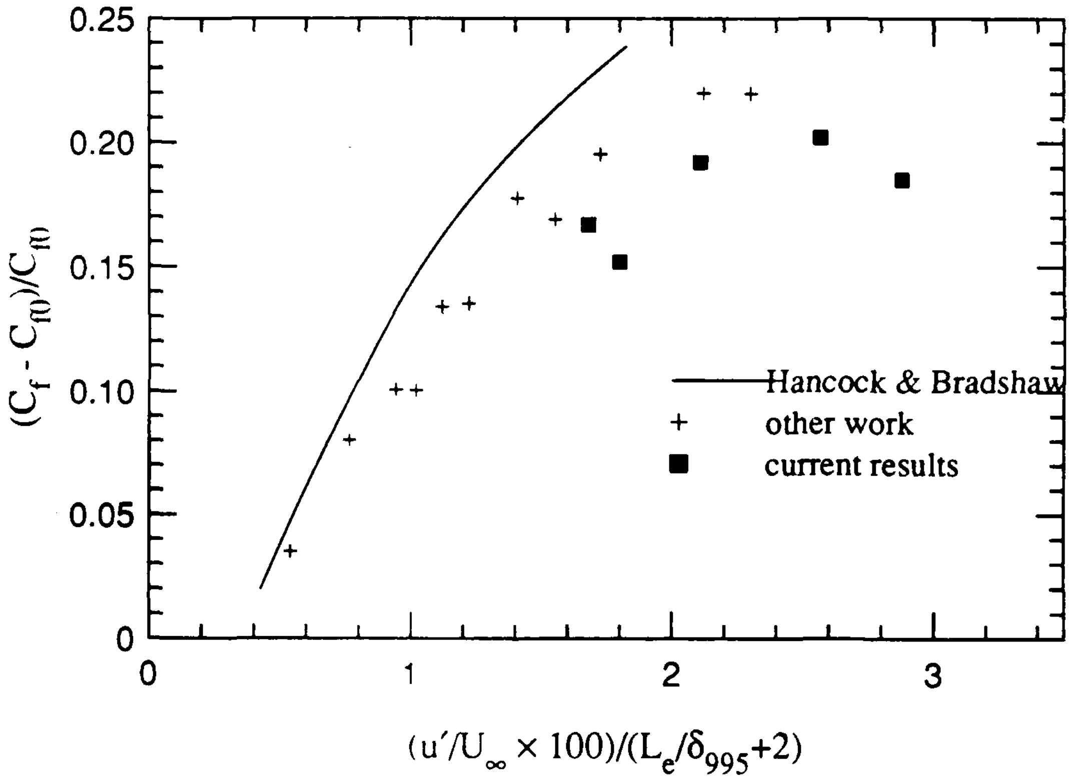

Fig. 2.1.2. Fractional increase in C_f for grid turbulence over a flat plate as a function of turbulence intensity and length scale.

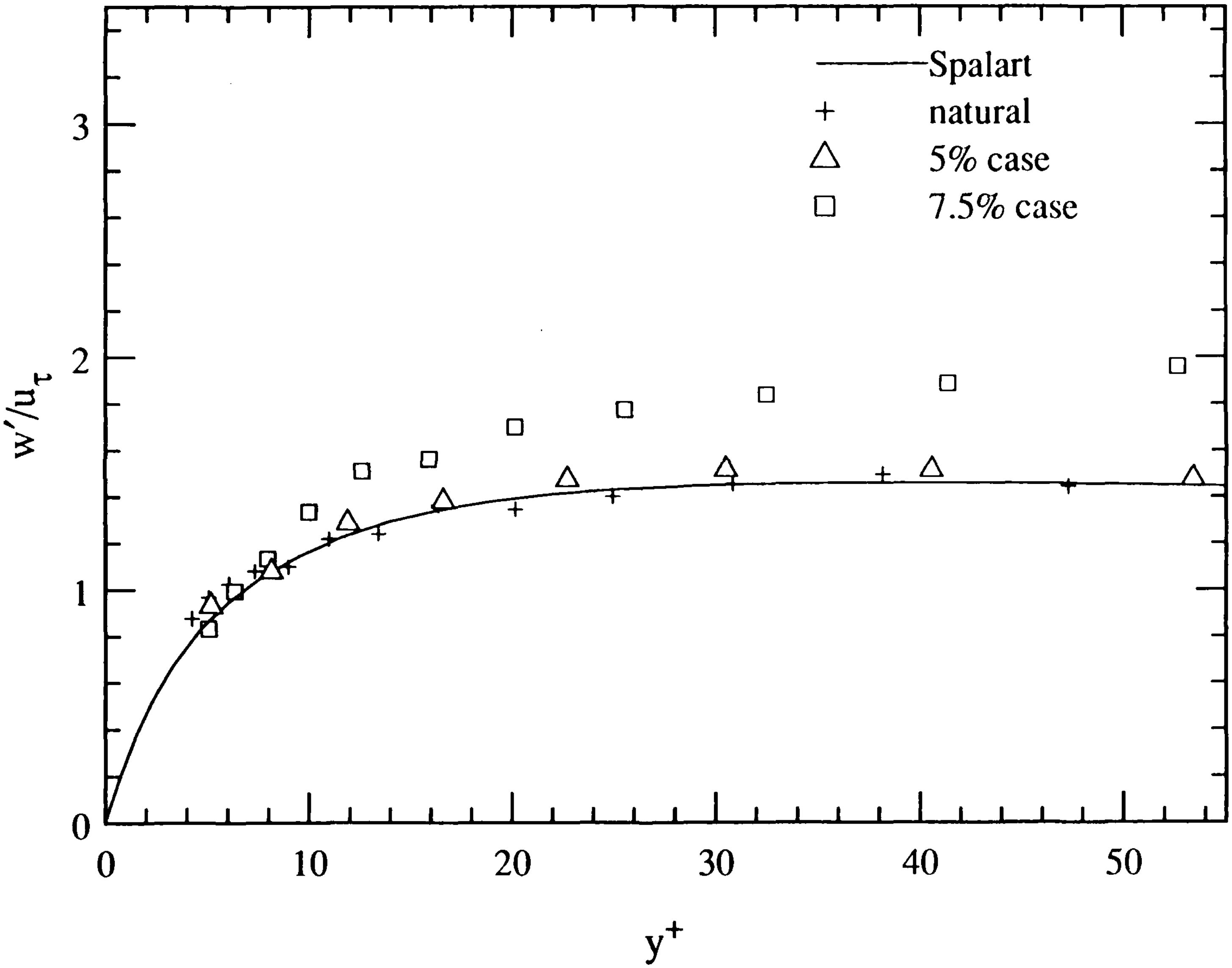

Fig. 2.1.3. Profiles of near-wall spanwise fluctuations.

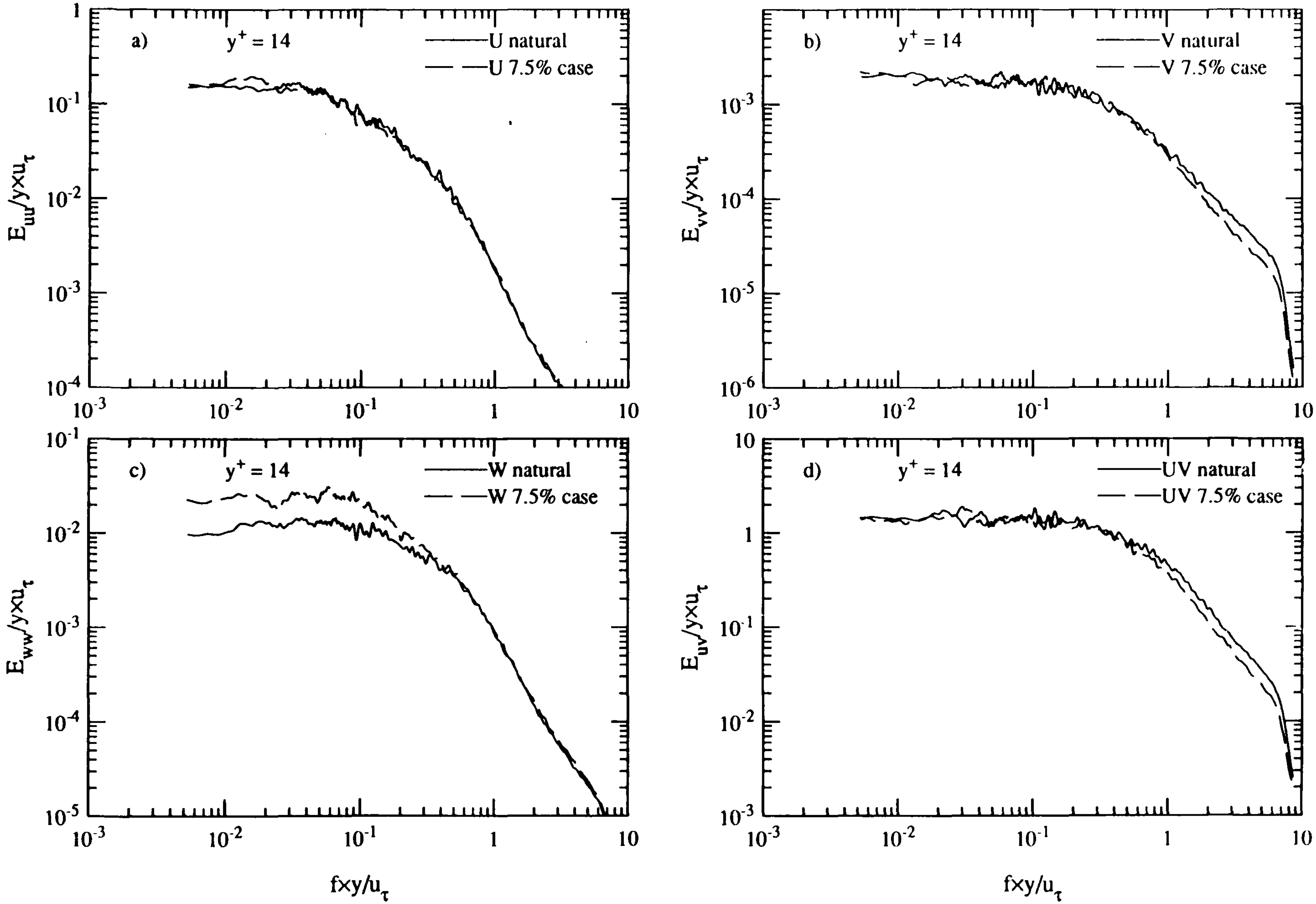

Fig. 2.1.4. Power spectra for natural and grid cases: a) Euu; b) Evv; c) Eww; d) Euv

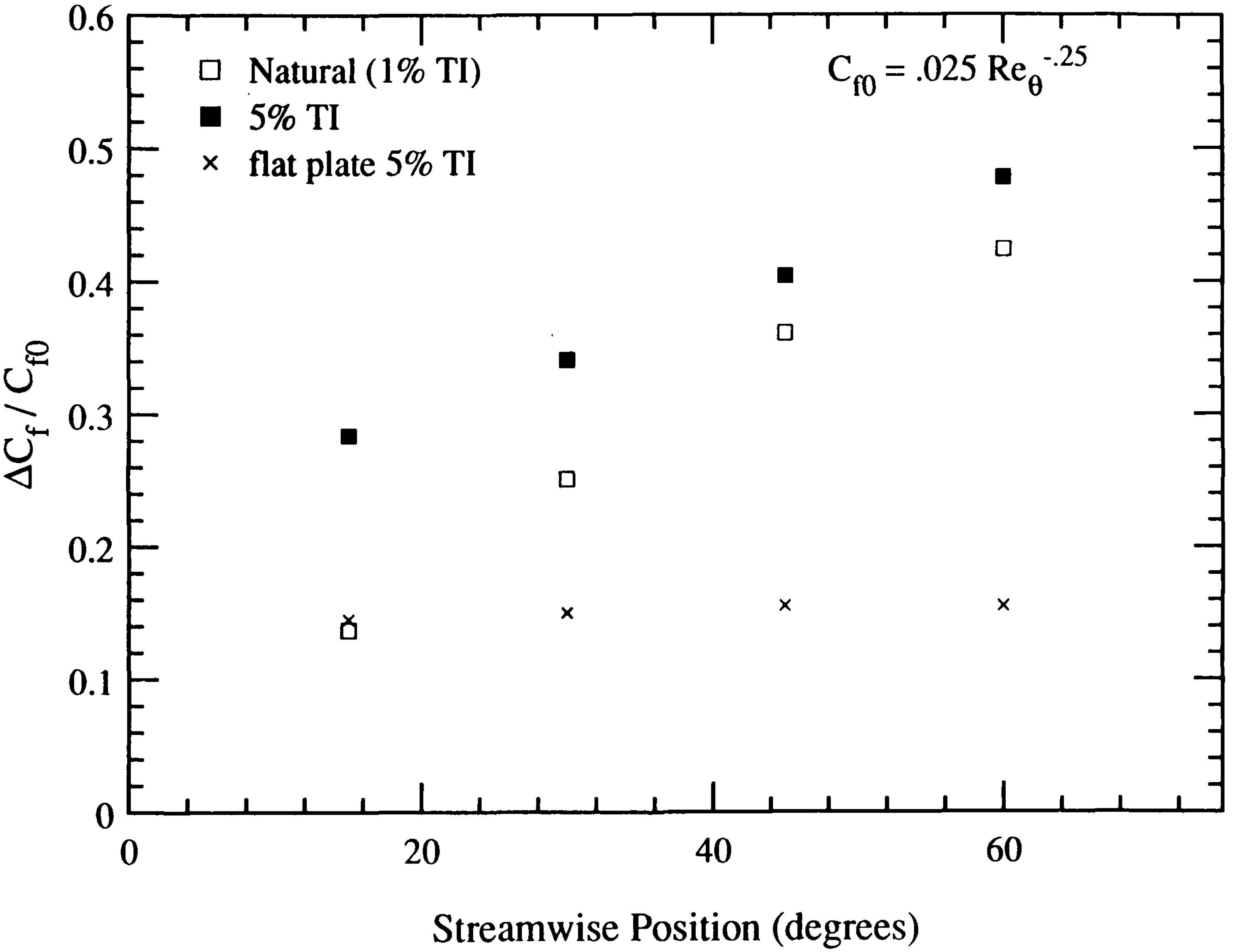

Fig. 2.1.5. Fractional increase in C_f through curve, with and without grid present. Increase in C_f for flat plate also shown.

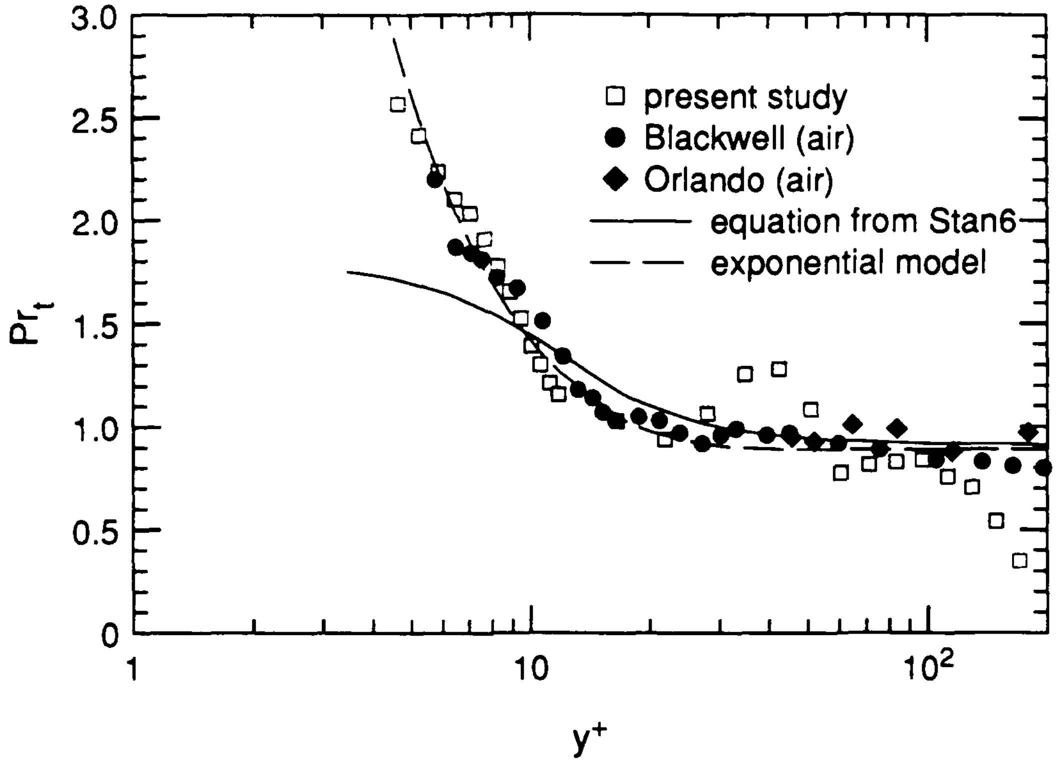

Fig. 2.2.1. Near-wall distribution of turbulent Prandtl number.

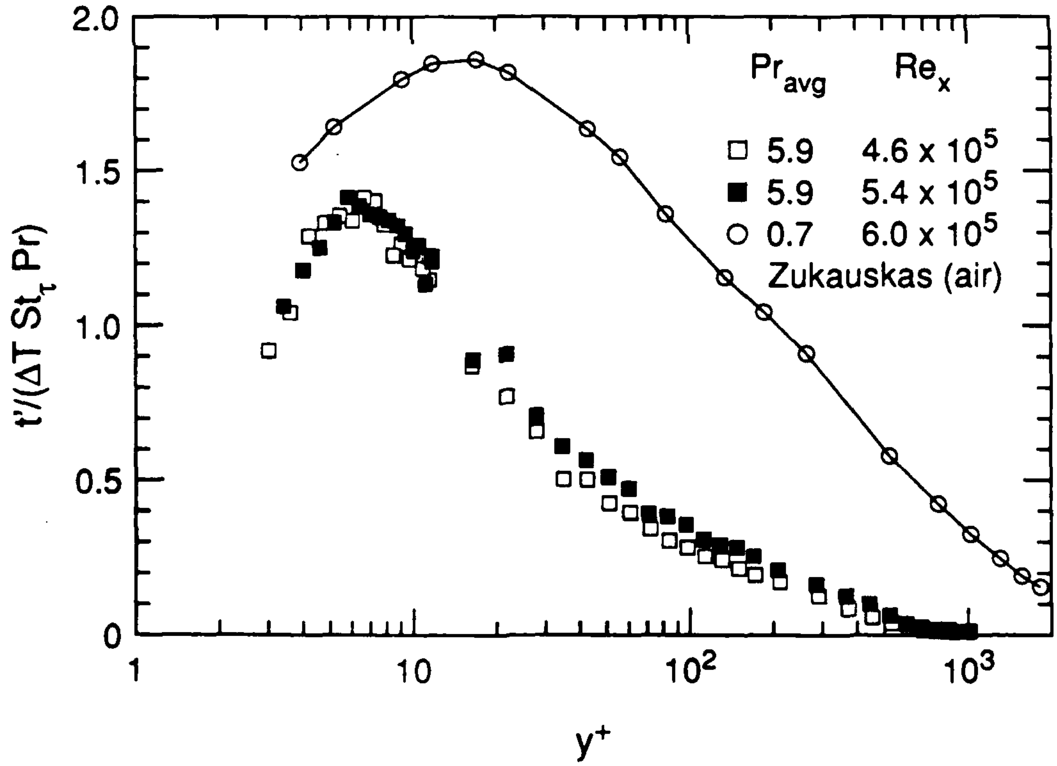

Fig. 2.2.2. Distributions of fluctuating temperature for water and air.

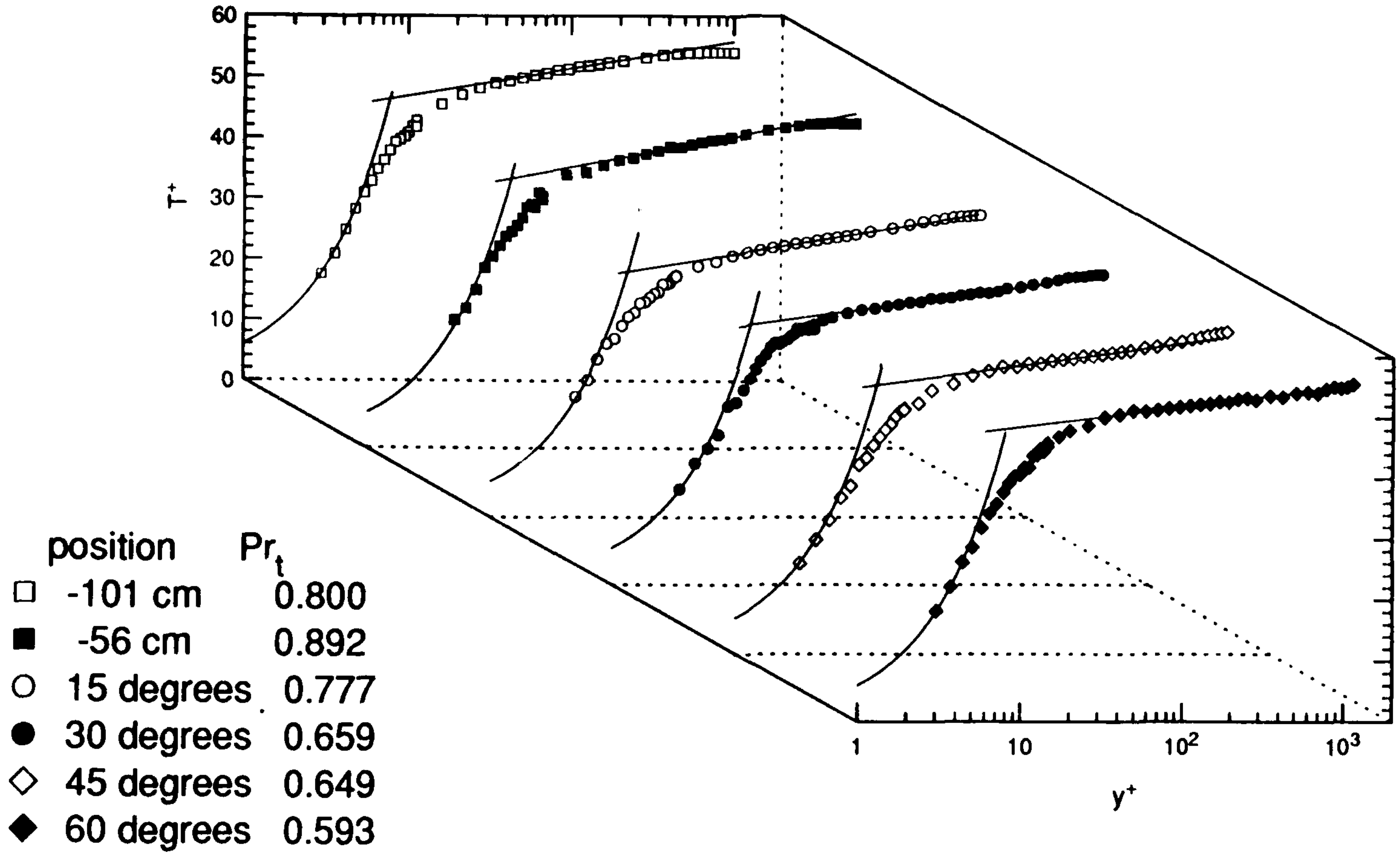

Fig. 2.2.3. Streamwise evolution of mean temperature profiles in inner-layer coordinates.

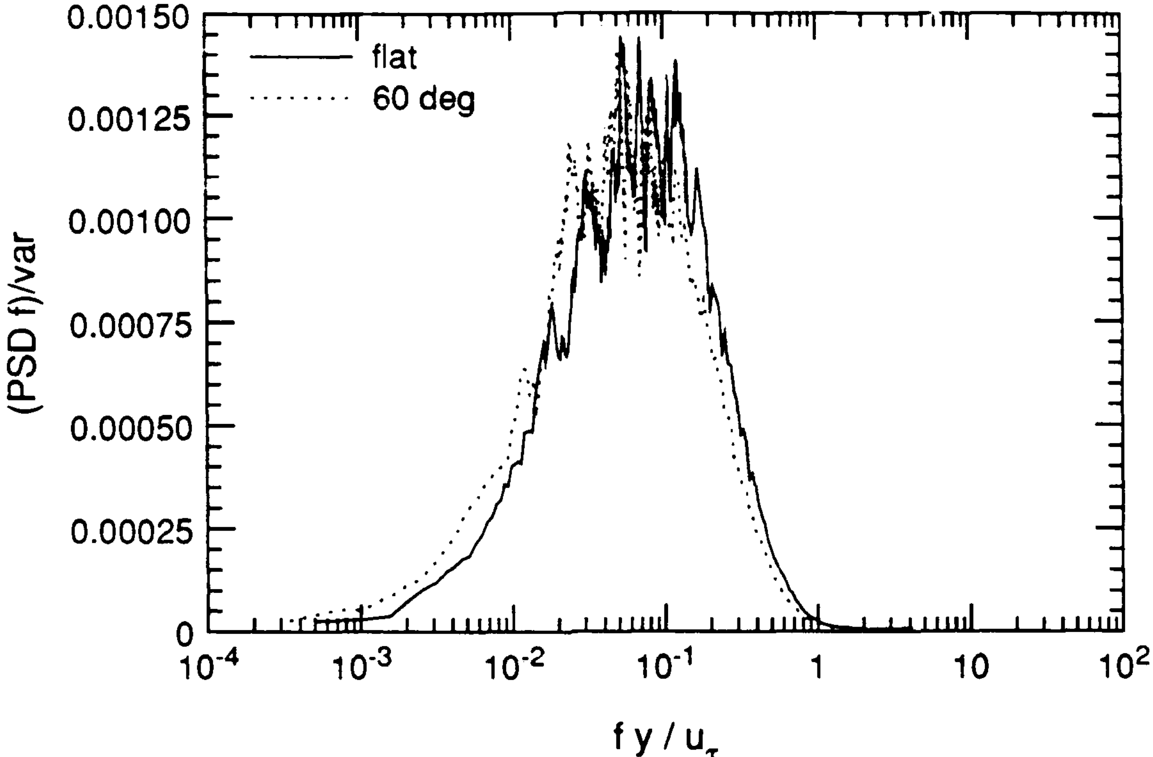

Fig. 2.2.4. Comparison of sublayer temperature spectra.

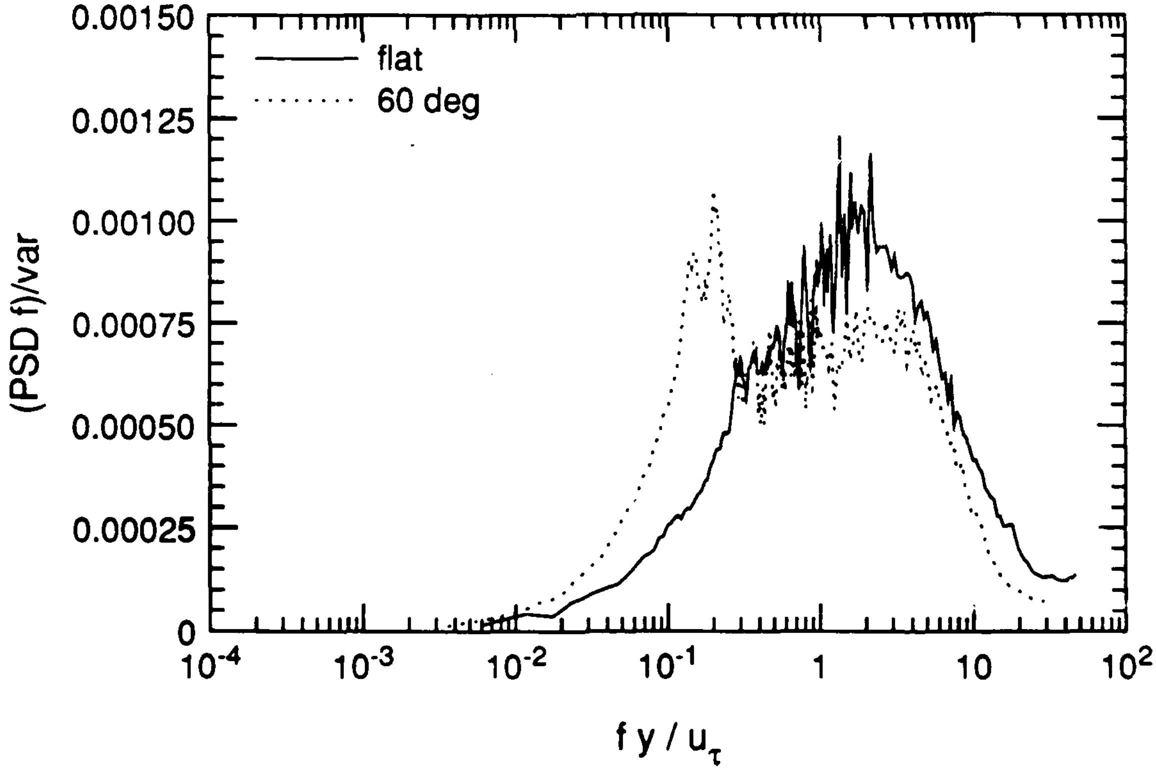

Fig. 2.2.5. Comparison of log layer temperature spectra.